

Violation of Bell inequalities by photons more than 10 km apart

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A Franson-type test of Bell inequalities by photons 10.9 km apart is presented. Energy-time entangled photon-pairs are measured using two-channel analyzers, leading to a violation of the inequalities by 16 standard deviations without subtracting accidental coincidences. Subtracting them, a 2-photon interference visibility of 95.5% is observed, demonstrating that distances up to 10 km have no significant effect on entanglement. This sets quantum cryptography with photon pairs as a practical competitor to the schemes based on weak pulses.

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Quantum theory is nonlocal. Indeed, quantum theory predicts correlations among distant measurement outcomes that cannot be explained by any theory which involves only local variables. This was anticipated by Einstein, Podolski and Rosen [1] and by Schrödinger [2], among others, and first demonstrated by John Bell in 1964 with his now famous inequality [3]. However, the nonlocal feature cannot be exploited for superluminal communication [4]. Hence, there is no contradiction with relativity, though there is clearly a tension. Physicists disagree about the significance and importance of this tension. This led Abner Shimony to name this situation "peaceful coexistence between quantum mechanics and relativity" [5].

Why should one still bother about quantum nonlocality despite that all experiments so far are in agreement with quantum theory [6,7]? The traditional motivations are based on fundamental questions on the meaning and compatibility of our basic theories, quantum mechanics and relativity: to date, no experiment to test Bell's inequality has been loophole free [8–10] and no experiment so far has directly probed the tension between quantum non locality and relativity. Recently, additional motivations to investigate quantum non-locality arose based on the potential applications of the fascinating field of quantum information processing: all of quantum computation and communication is based on the assumption that quantum systems can be entangled and that the entanglement can be maintained over long times and distances [11].

In 1997 we have demonstrated that two-photon correlations remain strong enough over 10 km so that a violation of Bell inequalities could be expected [12]. In this letter we report on a new experiment using two-channel analyzers in which all 4 coincidence rates have been measured simultaneously, thus allowing to obtain directly the correlation coefficient that defines the Bell inequalities. Our experiment demonstrates a violation of Bell's inequalities with photons more than 10 km apart [13], even without subtracting the accidental coincidences. In addition, an experiment with three interferometers, two on one end and the third at the other end (10 km away) is

presented. The two nearby interferometers analyse the incoming photons randomly, the choice being made by a passive beam splitter. This setup enables to test directly the CHSH form of Bell-inequalities [14]. Our experiment establishes also the feasibility of quantum cryptography with photon pairs [15] (in opposition to weak coherence pulses) over a significant distance.

For our Franson-type test of Bell inequalities [16], we produce energy-time entangled photons by parametric downconversion (Fig. 1). Light from a semiconductor laser with an external cavity (10 mW at 655 nm, $\Delta\nu < 10\text{MHz}$) passes through a dispersion prism P to separate out the residual infrared fluorescence light and is focused into a KNbO_3 crystal. The crystal is oriented to ensure degenerate collinear type I phasematching for signal and idler photons at 1310 nm [17]. Behind the crystal, the pump light is separated out by a filter F (RG 1000) while the passing down-converted photons are focused (lens L) into one input port of a standard 3-dB fiber coupler. Therefore half of the pairs are split and exit the source by different output fibers. Using a telecommunications fiber network, the photons are then analysed by all-fiber interferometers located 10.9 km apart from one another in the small villages of Bellevue and Bernex, respectively. The source, located in Geneva, was 4.5 km away from the first analyser and 7.3 km from the second, with connecting fibers of 8.1 and 9.3 km length, resp., as indicated in Fig. 1. Our interferometers use both the Michelson configuration and have a long and a short arm. In order to compensate all birefringence effects in the arms (i.e. to stabilize the polarization), we employ so called Faraday mirrors (FM) to reflect the light [18]. At the input ports, we use optical circulators (C). These devices guide the light from the source to the interferometer, but, thanks to the non-reciprocal nature of the Faraday effect, guide the light reflected back from the interferometer to another fiber, serving as second output port. The output ports of each interferometer are connected to photon counters [19]. We label the "direct" port as "+", the one connected to the circulator "-". To control and change the phases (δ_1, δ_2), the temperature of the interferometers can be varied.

Since the arm length difference is five orders of magnitude larger than the single photon coherence length, there is no single photon interference. However, the path difference in both interferometers is precisely the same, with a sub-wavelengths accuracy. Moreover, this imbalance is two orders of magnitude smaller than the coherence length of the pump laser. Hence, an entangled state can be produced where either both photons pass through the short arms or both use the long arms. Noninterfering possibilities (the photons pass through different arms) can be discarded using a high resolution coincidence technique [20].

To ensure symmetry for the two channels of each analyzer, we adjusted the count rates of the detectors attached to the same interferometer. Typical rates are 39.5 kHz including 26 kHz dark count rates. The classical signals from the photon detectors are transmitted back to Geneva. We measure the four different numbers of time-correlated events $R_{i,j}(\delta_1, \delta_2)$, ($i, j = \pm$), where i.e. R_{+-} denotes the coincidence count rate between the + labeled detector at apparatus 1 and the - labeled one at apparatus 2. (For further technical information we refer the reader to our full length paper [21].)

From these four coincidence count rates we compute the correlation function:

$$E(\delta_1, \delta_2) := \frac{R_{++}(\delta_1, \delta_2) - R_{+-}(\delta_1, \delta_2) - R_{-+}(\delta_1, \delta_2) + R_{--}(\delta_1, \delta_2)}{R_{++}(\delta_1, \delta_2) + R_{+-}(\delta_1, \delta_2) + R_{-+}(\delta_1, \delta_2) + R_{--}(\delta_1, \delta_2)} \quad (1)$$

and can determine the Bell parameter:

$$S = |E(d_1, d_2) + E(d_1, d'_2) + E(d'_1, d_2) - E(d'_1, d'_2)| \leq 2, \quad (2)$$

where d_i, d'_i ($i = 1, 2$) denote values of phases δ_i . The above inequality, known as Bell-CHSH inequality [14], is satisfied by all local theories. Quantum mechanics predicts a maximal value for the Bell parameter $S = 2\sqrt{2}$.

Another type of Bell-inequality was given by Clauser and Horne [22] for an experiment with polarizers. A similar argument can be applied to experiments using interferometers: if it is found experimentally that the single count rates are constant, and that $E(\delta_1, \delta_2) = E(\Delta)$ holds where $\Delta = (\delta_1 + \delta_2)$ is the sum of the phases in both interferometers, then Eq. 2 reduces to $S = |3E(\Delta) - E(3\Delta)| \leq 2$. Beyond that, if it is found that the correlation coefficient E is described by a sinusoidal function of the form $E = V \cos(\Delta)$ with visibility V , then the Bell parameter S becomes $S = V2\sqrt{2}$. Hence, observing a visibility V greater than $V \geq \frac{1}{\sqrt{2}} \approx 0.707$ will in this case directly show that description of nature as provided by quantum mechanics is unreconcilable with the assumptions leading to the Bell inequalities.

In a first experiment, we changed the path length differences of both interferometers simultaneously, but at different speeds. Comparing the correlation functions when both interferometers scan in the same direction,

both in opposite directions and when only one is scanning, we can confirm that in a Franson-type interferometer the fringes can be described by a sinusoidal function and depend on the sum of the two phases ($\delta_1 + \delta_2$). In addition, no phase dependent variation of the single count rates could be observed. Hence we can calculate the parameter S from the observed visibilities. In all cases we find values exceeding the limit given by the Bell-inequalities by at least 9 standard deviations (σ). The raw data for one of the best violations yield $S_{raw} = (0.853 \pm 0.009) \cdot 2\sqrt{2}$, corresponding to a violation by 16 σ . Most of the difference between this result and the theoretical prediction can be attributed to accidental coincidences [23]. Indeed, from the measured single count rates (39.5 kHz) and the coincidence window of (550 ± 10) ps one can estimate the accidental coincidence rate to be 25.7 ± 0.5 per 30 seconds (assuming that all events at both detectors are uncorrelated). This rate is in excellent agreement with the one we measured placing the coincidence window apart from the coincidence peak (26.4 ± 1.3 per 30 sec). Subtracting the accidental coincidences, we obtain $S_{net} = (0.955 \pm 0.01) \cdot 2\sqrt{2}$, corresponding to a violation of the inequality by 24.8 σ . Since the visibility of the correlation function after subtracting the accidentals is close to 1, one has to conclude that the distance does not affect the nonlocal aspect of quantum mechanics, at least for distances up to 10 km [24].

In a second experiment, we replaced one of the interferometers by two interferometers connected to the fiber from the source by a fiber coupler (i.e. a beam splitter). These two interferometers, however, used no circulators, hence only one detector per interferometer could be used. For this reason we can only measure two of the four coincidence count rates needed to calculate the correlation function (Eq. 1). To infer from the measured functions to the correlation function we thus have to assume the same symmetry between the coincidence functions as we found in the experiment described before. With this quite natural assumption, we can evaluate the correlation coefficients $E(d_1, d_2)$ and $E'(d'_1, d_2)$ at the same time, hence for exactly the same setting δ_2 . Fig. 2 shows the correlation coefficients observed when changing the phase δ_2 in the Bernex interferometer. We find again sinusoidal functions. Visibilities are about 78% without and about 96 % with subtraction of accidental coincidences. (The smaller raw visibility compared to the first experiment is due to 50 % additional losses in the coupler [25].) We can now directly evaluate the value of the Bell parameter S (Eq. 2) from the correlation coefficients for two different values d_2, d'_2 . For the indicated points we find $S_{raw} = 2.38 \pm 0.16$ and $S_{net} = 2.92 \pm 0.18$ leading to a violation of 2.4 respectively 5.1 standard deviations and confirming once again the quantum mechanical predictions.

Assuming that the passive coupler randomly selects which interferometer analyses the photon, this experiment can be considered as involving truly random choices for the analyser settings as required to close the locality

loophole [9], at least on one side of the experiment. Since we find the same net visibility as in the first experiment, we can infer that the random choice at the beamsplitter does not change the result of the measurement. One could argue that the choice is not really random, since the assumed local hidden variable could determine into which interferometer the photon is guided. Note however, first, that it is difficult to think of a better random number generator than a quantum one (based e.g. on a beam splitter as in our case), next that if the hidden variable could determine a preferred interferometer, it could equally well determine whether the photon is detected at all or remains undetected. This is the basis of the detection loophole, an interesting possibility still open for local theories [8].

Another way to look at our experiments is quantum cryptography based on entangled particles [15]. The quantum bit error rate (QBER) [26] of this scheme is related to the visibility V before removal of the accidental coincidences: $\text{QBER} = \frac{1-V}{2}$. Note that subtracting the accidentals is impossible for quantum cryptography, as there is no way to determine which coincidence counts are accidental and which are due to a photon pair. From our measured raw visibility of 85.2% we infer a QBER of 7.4%. This is higher than the QBER obtained in experiments using weak pulses [11]. Nevertheless, our result demonstrate that it is promising for practical implementation, not so far from the schemes working with weak pulses. A fast switching in order to really exchange a key still has to be implemented. This switching can be done either by a phase modulator or, as we did in our last experiment, by using a fiber coupler connected to two interferometers with appropriate phase differences. The advantage of the latter setup is that no fast random generator and switching electronic is necessary. However, since the QBER increases with increasing losses, this setup would in our case be limited to around 10 km, a distance which is determined by the number of created photon pairs, overall losses and detector performance. A better way to do entanglement-based quantum cryptography would be to use a source employing non-degenerate phasematching in order to create correlated photons of different wavelengths, one at 1310 nm, the other one around 900 nm. This would allow to use more efficient and less noisy silicon photon counting modules to detect the photons of the lower wavelength. To avoid the high transmission losses of photons of this wavelength in optical fibers, the interferometer(s) measuring these photons could be placed next to the source. First investigations show that quantum cryptography over tens of kilometers should be possible. It is interesting to note that besides ensuring the security of entanglement based quantum cryptography, the Bell inequality is even connected to the one qubit application of quantum cryptography: a quantum channel can be used safely if and only if the noise in the channel is small enough to allow a violation of Bell inequality [27].

As already mentioned in the introduction, no experi-

ment up to date has been loophole free. Assuming that our results are not affected by the presence of these loopholes, this experiment demonstrates that energy-time entanglement is robust enough to manifest itself in the violation of Bell inequality by photons more than 10 km apart. It opens also the door to several new possibilities: close the locality loophole, densecoding [28], entanglement swapping [29] and quantum teleportation [30] at large distances as well as for entanglement based quantum cryptography. There is also another interesting proposal: set the two analyser in motion such that each analyser in his own inertial frames measures the photon pairs first [31].

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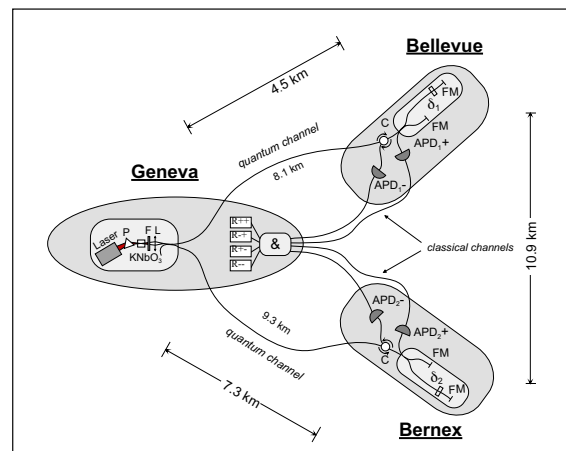


FIG. 1. Setup for experiment 1. See text for detailed description

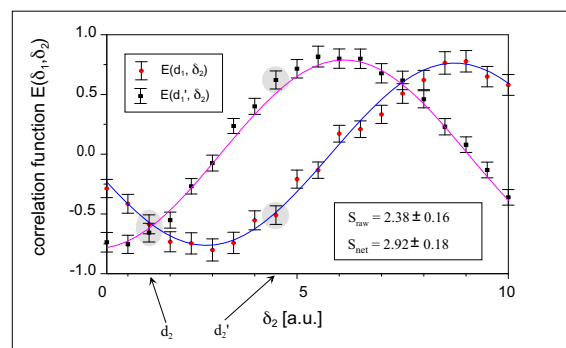


FIG. 2. Result for experiment 2: The correlation functions $E(d_1, \delta_2)$ and $E(d'_1, \delta_2)$ are plotted as a function of phase δ_2 . From the four indicated points one obtains $S_{raw}=2.38 \pm 0.16$ and $S_{net}=2.92 \pm 0.18$, leading to a violation of the CHSH-Bell-inequality of 2.4 and 5.1 standard deviations, respectively.